CHAPTER 1

INTRODUCTION

1-1. Purpose. This manual provides guidance for storm surge analysis and design water level determinations in coastal areas.

1-2. Applicability. This manual applies to all HQUSACE/COE elements and field operating activities (FOA) engaged in civil works function.

1-3. References.

a. ER 1110-2-1453

b. Shore Protection Manual (SPM), 4th ed., Vols I and II, U. S. Army Engineer Waterways Experiment Station, Coastal Engineering Research Center. Available from Superintendent of Documents, U. S. Government Printing Office, Washington, D.C. 20402

1-4. Bibliography. Bibliographic items are cited in the text by numbers (item 1, 2, etc.) that correspond to items in Appendix A. Where any reference or bibliographic item contains information that conflicts with this manual, the provisions of this manual shall govern.

1-5. Units and Datums. The English system of units is generally used throughout this manual; however, the equivalent metric units are supplied in some cases. Unless otherwise noted, elevations of the seabed, land topography and water level elevations are based on the National Geodetic Vertical Datum (NGVD) of 1929.

1-6. Overview of Manual.

a. Coastal engineering studies often require estimation of surges induced by tropical storms and other accompanying water level changes in coastal regions. Accurate prediction of these abnormal water level rises during storm periods is essential for proper planning and design of coastal works, assessing the elevation and extent of coastal flooding and developing evacuation plans. Basic principles and estimating procedures pertaining to storm surges and related effects are presented.

b. Flood potential due to tropical storms is greater for coastal regions along the Atlantic and Gulf Coasts of the United States and storm surge analyses for these areas are emphasized. However, the methods and procedures presented are generally applicable to the Pacific Coast, Hawaiian Islands and the Great Lakes.

c. This manual is general in nature and therefore requires that good engineering judgment be exercised when applying the methods and procedures presented herein to actual storm surge problems. Although a complete understanding of the underlying theoretical concepts is not essential to performing storm surge estimates, a basic understanding of hydrodynamic processes, wave mechanics, statistics and computational hydraulics is needed to ensure proper application.

d. Four chapters are included in this manual. Chapter 1 provides an introduction to water level variations in coastal waters, storms originating over ocean areas, storm surge generation and its effects in coastal areas, and the theory of water motions applicable to storm surge analysis. Chapter 2 presents two different approaches for estimating storm surge. One approach involves prediction of the abnormal water level rises based on an analysis of historical data; and the other approach involves calculating the rises based on numerical computational procedures. Statistical techniques are presented in Chapter 3 to provide a means for estimating the magnitude and frequency of occurrence of abnormal water levels in coastal regions when using either of the prediction approaches. Finally, Chapter 4 presents methods and procedures for including particular storm and nonstorm related effects in estimating the design water level.

e. Seven appendixes are also included in this manual. Appendix A contains a list of the references cited; and Appendix B lists the mathematical symbols used and their corresponding definitions. The remaining appendices provide information with regard to special computational procedures, example problems and tables. Also a glossary is provided at the end of the manual for the purpose of defining various terms used herein.

1-7. Nature of Tropical Storms. Many dangerous and destructive tropical storms have occurred along the Atlantic and Gulf Coast areas of the United States in this century alone. Some were extremely severe, others less severe, but all were destructive. Of these storms, the great storm of September 1900 stands above all others because it took the lives of more than 6,000 people, mostly on Galveston Island. Had major steps not been taken since 1900 with respect to storm warnings and deployment of coastal flood protection systems it is obvious the death toll would have been substantially higher than has occurred as a result of subsequent severe storms. In addition to the loss of lives in the past few decades, tropical storms have also caused property damages that ran into the billions of dollars. It has been estimated that Hurricane Carla (1961) caused damages in excess of $400 million (based on 1961 price levels) and flooded more than 1.5 million acres of land. In many coastal areas a severe storm may raise the water level in excess of 15 feet above the normal level on the open coast and even higher in estuaries and other inland areas. The elevated coastal waters, due to surges, provide a higher level in which short period surface waves can propagate, thus subjecting beaches and structures to wave forces not ordinarily experienced. Surges coupled with the action of wind generated surface waves are responsible for the greatest damage to coastal areas. They can destroy or severely damage dwellings, business establishments, commercial properties and docking facilities, erode beaches, displace stones or concrete armor units on jetties, groins or breakwaters, undermine structures via scouring, cut new inlets through barrier beaches and shoal navigational channels. The latter shoaling problem can result in hazards to navigation thus impeding vessel traffic and hampering harbor operations.

1-8. Water Level Variations. The term "water level" is used herein to indicate the mean elevation of the water surface when averaged over a sufficient period of time (about 1 to 2 minutes) to eliminate the clearly distinguishable short period surface waves. Water level variations in coastal zones are produced by a number of distinct causes. These are identified as:

a. Storm Surge. A rise or possible fall of the normal water level in coastal waters due to the interaction between a storm and the underlying water surface.

b. Wave Setup. Superelevation of the water surface above the normal water level due to onshore mass transport of water by wave action alone.

c. Astronomical Tides. An almost periodic rising and falling of the water that results from gravitational attraction of the moon, sun and other astronomical bodies acting on the rotating earth.

d. Secular Fluctuations. Long term trends in sea level due to such causes as melting of the polar ice caps, large scale isostatic adjustments of the earth's crust and local subsidence.

e. Tsunamis. A long-period wave caused by an earthquake or underwater disturbance such as a volcanic eruption or a landslide. The spectrum of tsunamis covers a range of periods from several minutes to an hour.

f. Climatological Effects. Seasonal or long-term changes in the water level which result from seasonal heating or cooling of the water column or from seasonal variations in the mean wind fields.

g. Seiches. A standing wave oscillation in enclosed and semi-enclosed water bodies that can continue after the cessation of the originating force. Seiches are long period waves that can be induced in bays and some ocean basins by changes in atmospheric pressure or by winds. These standing waves are analogous to the sloshing back and forth in a bathtub once the water is disturbed. Energy of this wave is dissipated primarily by friction or by radiation to an adjacent sea in the case of a bay.

Although the focus in this manual is storm surge, the design engineer will need to consider such effects as wave setup in nearshore regions, astronomical tides and possible secular fluctuations, climatological changes and seiches in combination with storm surge to determine the total water level at a project site. Tsunamis may be disregarded in the determination of total water level during the passage of a storm. Astronomical tides can have a pronounced effect on the total water level rise in some coastal areas coincident with storm surge. Tides are a well documented phenomenon and can be predicted with considerable accuracy at locations where observations are available for one year or more. Because tide prediction methods have been published by a number of investigators applicable to coastal waters of the United States (items 18, 24, 54, 59 of Appendix A) no attempt will be made herein to cover the methods. Tide predictions are made available for many coastal locations by the National Ocean Survey, National Oceanic and Atmospheric Administration (NOAA).

1-9. Storms.

a. A storm is an atmospheric disturbance characterized by one or more low pressure centers and high winds. These disturbances frequently are accompanied by precipitation of varying intensity. An important distinction is made in classifying storms: a storm originating in the tropics is called a "tropical storm;" a storm resulting from the interaction of a warm and a cold front is called an "extratropical storm". A severe tropical storm is referred to as a "hurricane" or "tropical cyclone" when the maximum sustained winds equal or exceed 75 miles per hour. Unlike extratropical storms and less severe tropical storms, hurricanes are well organized in respect to the wind patterns. The wind patterns of a hurricane are, more or less, circular with winds revolving counterclockwise (in the northern hemisphere) about the storm center or eye, not necessarily the geometric center. Winds in hurricanes blow spirally inward and not along a circle concentric with the storm center. Wind isovel patterns and wind directions are illustrated as shown in Figure 1-1a. The eye is characterized as an area of low atmospheric pressure and light winds. `Atmospheric pressure increases with distance from the eye to the periphery or outskirts of the hurricane. Highest wind speeds usually occur in the right quadrants of the hurricane at a distance varying from about 4 to 70 nautical miles from the center. However, in all directions outward from the eye of the hurricane, the wind speed increases rapidly to a maximum and then decreases with distance to the outskirts of the storm. The best single index for estimating the surge potential of a hurricane is the atmospheric pressure within the eye and if referred to as the "central pressure index" (CPI). In general, the lower the CPI, the higher the wind speeds. Other important parameters of a hurricane with regard to the surge potential are the "radius of maximum winds" (R) which is an index of the size of a storm, the speed of forward motion of a storm system (V_f) and the track direction (θ) in which a hurricane moves (measured clockwise from the north).

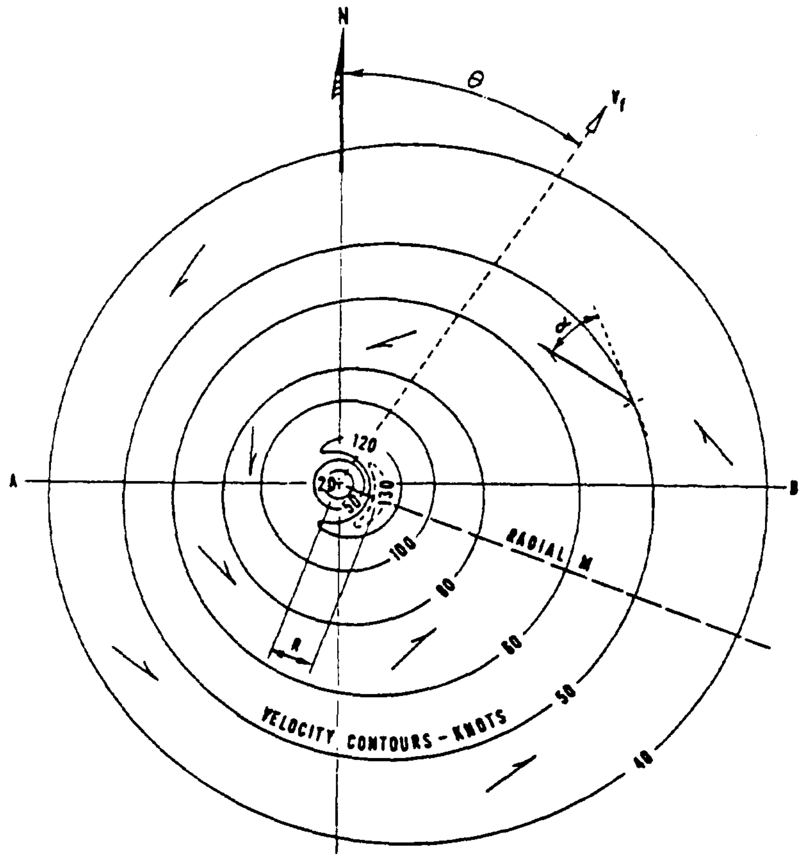
b. Pronounced water level changes due to tropical storms may occur anywhere along the gulf coast and anywhere from Cape Cod to the southern tip of Florida on the east coast of the United States. Occasionally the southern coast of California on the west coast experiences changes in water level as a result of tropical storms but these are usualy small due to the narrow continental shelf in that region. Large changes in water level may occur along the northern part of the east coast of the United States as a result of extratropical storms in which strong winds blow in a north-easterly direction. These storms are commonly referred to as "Northeasters".

c. Northeasters are important from the standpoint of design considerations on the east coast. However, an acceptable technique for specifying the wind fields for design storms is not presently available. It is expected that such a technique will become available and be included in subsequent revisions of this manual.

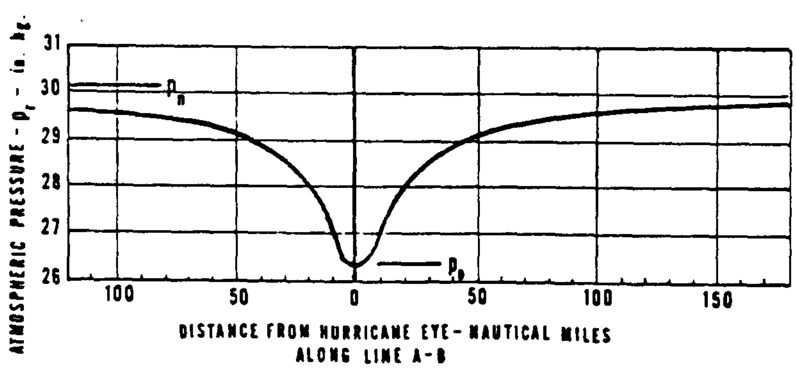
d. In engineering studies hypothetical hurricanes are frequently used to assess the levels of flooding for a predetermined degree of severity. These storms are derived based on the specification of meteorological parameters R, V_f, P_o, P_n, θ, and α in which P_o is the central pressure, P_n is the peripheral pressure and α is the inflow angle (see Figure 1-1b). It has been the general practice to use invariant meteorological parameters for any given hypothetical hurricane prior to the storm making landfall. Thus such storms are classified as steady state hurricanes. Particular hypothetical hurricanes which have been used in some engineering investigations are referred to as the Standard Project Hurricane (SPH) and Probable Maximum Hurricane (PMH). The SPH is defined as a hurricane having a severe combination of values of meteorological parameters that will give high sustained wind speeds reasonable characteristic of a specified coastal location. A PMH, on the other hand, is defined as a hurricane having a combination of values of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location. Recurrence intervals for the SPH and PMH are not assigned due to the uncertainties involved in establishing their frequencies. The SPH is frequently used in the design of coastal works where a high degree of protection is required while the PMH is generally used solely in connection with the design of nuclear power generation plants sited in coastal areas.

e. Hypothetical hurricanes with more frequent recurrence intervals than the SPH may also be used to estimate the frequency and levels of flooding. The flood frequencies are established by calculating the water levels resulting from a rather large number of different hypothetical hurricanes and assessing the recurrence intervals by application of the joint probability method. Methodology is presented in Chapter 3 for determining flood frequencies.

1-10. Storm Surge Generation Processes. In shallow seas there are at least five distinct processes during passage of a storm which alter the water levels in the coastal zone (item 23 of Appendix A).



a. Wind isovel pattern and pertinent parameters



b. Pressure profile

Figure 1-1. Sketch showing hurricane parameters.

These processes are identified as:

a. direct wind effect

b. atmospheric pressure effect

c. effect of Earth's rotation

d. rainfall effect

e. wave setup effect

(1) Direct Wind Effect. The largest incremental change in water level, considering all contributing processes in storm surge generation, is attributed to the direct effects of wind. A wind blowing over the water surface exerts a horizontal force on the surface water and in shallow water induces a current in the general direction of the wind. The force exerted on the water by the wind is partly due to inequalities of air pressures on the upwind and downwind side of gravity waves and partly due to shearing stresses at the water surface. It is usually presumed that the wind stress is proportional to the square of the wind speed in which the coefficient of proportionality is usually assumed as a constant or assumed to vary with the wind speed. Variation of the coefficient is usually justified on the basis that the sea surface becomes increasingly rough with increasing wind speeds (see item 19 of Appendix A).

(2) Atmospheric Pressure Effect. Atmospheric pressure may vary significantly over the ocean during periods of severe tropical storms. Water levels rise in regions of low pressure and fall in regions of high pressure. Calculations of storm surge in the coastal zone have shown that atmospheric pressure differences can contribute as much as 2 to 3 feet to the peak surge.

(3) Earth's Rotation Effect. Due to the Earth's rotation a deflecting force, referred to as the Coriolis force, is produced which acts to the right of any current (at right angles to the

velocity vector) in the Northern Hemisphere. The Coriolis force is purely a deflecting force and it cannot by itself change the speed of the water but only its direction. If the coast is to the right of the current, then this leads to an increase in the sea level at the coast and conversely a decrease in sea level if the coast is to the left of the current.

(4) Rainfall Effect. Observations from past storms reveal that large quantities of rainfall may occur when hurricanes move over the continental shelf and cross coastal areas. After landfall of a hurricane, a storm system or remnant hurricane may also dump large amounts of rainfall as it moves many miles inland. In general, rain falling on the open sea has a minimal effect on the surge produced on the open coast due to the areal extent of the sea and mechanisms involved in establishing the gradient over the shelf. However, in bays, estuaries and in areas of low-rising water levels, rainfall can contribute significantly to the total rise. Also, the flood levels in these areas may be augmented as a result of rainfall runoff from adjacent land areas. An additional effect of rainfall on storm surge generation is caused by windblown raindrops striking the water surface. These wind-propelled raindrops exert a horizontal force on the water surface in the general direction of the wind due to their angle of entry at the air-sea interface.

(5) Wave Setup Effect. The sea level in nearshore regions may be increased due to the action of surfaced waves in the surf zone. When waves break offshore on a line more or less parallel to the beach, a significant quantity of water is transported shoreward causing a runup on the beach face. Water moved shoreward due to waves breaking cannot return offshore as rapidly or effortlessly as it was brought shoreward. As a consequence of these differences in transport rates, water is piled up at the beach. A gradient is thus established which extends from where the waves break to the shore. This piling up of water near the shore is referred to as "wave setup".

1-11. Storm Surge on the Open Coast.

a. A tropical storm originates over the ocean and as the storm grows in size and intensifies a considerable amount of energy is transferred from the atmosphere to the water. In deep ocean areas most of the energy imparted to the water results primarily in the generation of surface waves, but when the storm moves into the shallower waters over the continental shelf a current is induced in the general direction of the wind. When wind blows shoreward, water is transported in the upper layers of the sea surface over the continental shelf to the coast, and water is returned seaward along the bottom layers above the seabed. Water returning seaward under the influence of gravity is slower and impeded by bottom friction, resulting in a gradient extending from the general vicinity of the edge of the continental shelf to the shoreline. At a state of equilibrium the gradient remains constant and thus the water brought shoreward is equal to the water returned seaward. The highest water level produced by a storm at any coastal location in the absence of astronomical tide effect is referred to as the "maximum surge" while the highest water level produced during the course of the storm is referred to as the "peak surge". For hurricanes moving on a path, more or less, perpendicular to a coast with offshore contours approximately parallel to the coast, the peak surge will normally occur at or near the point where the region of maximum winds intersects the shoreline--a distance approximately equal to R or the radius measured from the storm center to the region of maximum winds to the right of the storm center.

b. Abnormal water levels produced by storms on the open coast can persist over a period of several days and affect the water levels over hundreds of miles of coastline. These effects are demonstrated for Hurricane Carla (1961). The track of this severe tropical cyclone is shown in Figure 1-2 together with the hourly positions of the storm center. Figure 1-3a shows the duration in which water levels were affected on the open coast at Galveston, Texas, approximately 115 miles to the right of the storm track at the time of landfall. The total water level as depicted in Figure 1-3b shows only the storm surge which was obtained by subtracting the predicted tide from the total water level. Figure 1-4 shows the high water marks and extent of flooding based on a post-storm survey for Hurricane Carla.

1-12. Modification of Storm Surge. A disturbance on the continental shelf due to the passage of a storm will propagate into any estuary or bay on the coastline in a manner generally analogous to an astronomical tide. The amount of water transported from sea to estuary depends on the size of the opening (i.e., through the inlets or by overtopping low-lying land masses or barrier islands), difference in heads between the two water bodies and duration of the disturbance. The wind field over the embayment is primarily responsible for tilting the water surface across the estuary. Winds blowing inland will allow more water to enter the estuary and pile up water at the head of the estuary, while winds blowing seaward will either restrict the flow of water from sea to estuary or transport water from estuary to sea depending on the slope of the water surface across the opening. In shallow estuaries, it is possible that the upwind side of the estuary will completely dry-up during a certain phase of the storm while piling water up at the downwind shore. The location of highest water levels in estuaries is usually constantly changing during the passage of a hurricane due to the circular wind patterns and storm motion. The rate and degree of change in water level depend on the track that the hurricane takes upon passing the embayment. Surge levels in estuaries can be considerably higher than those on the open coast when wind drives the water into a converging section of the estuary. Convergent sections are predominantly at those locations where streams empty into the estuary. In general, the increase in water surface elevation at any location in an estuary depends on the amount of water transferred from the sea, basin geometry, wind speed and direction, length of wind fetch, rainfall, rainfall runoff and possible water transported into the system by rivers. Surge levels are further modified when high water on the open coast or in estuaries flood onto adjacent low-lying land areas. At some locations the surge can cause water to move inland for considerable

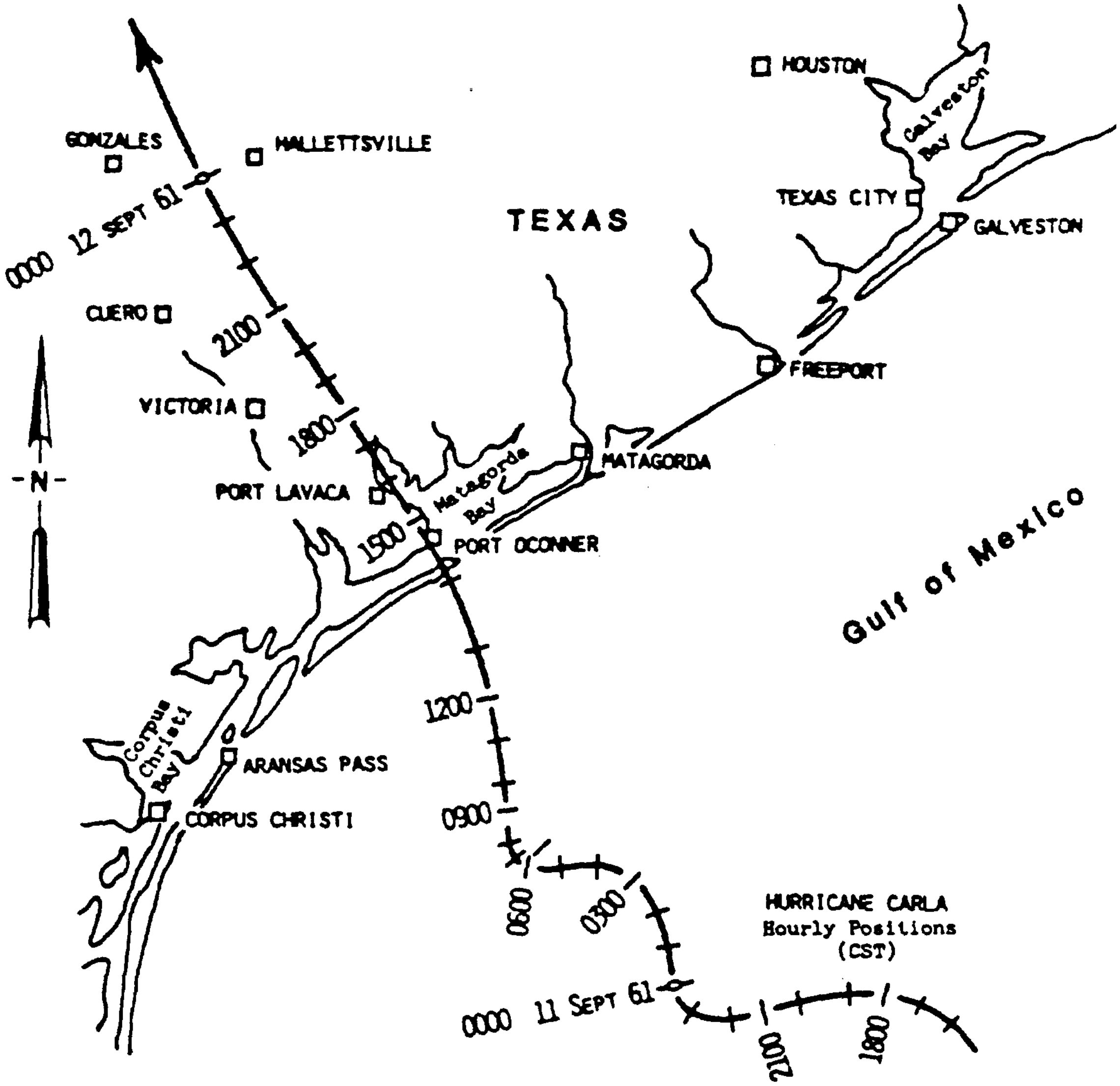
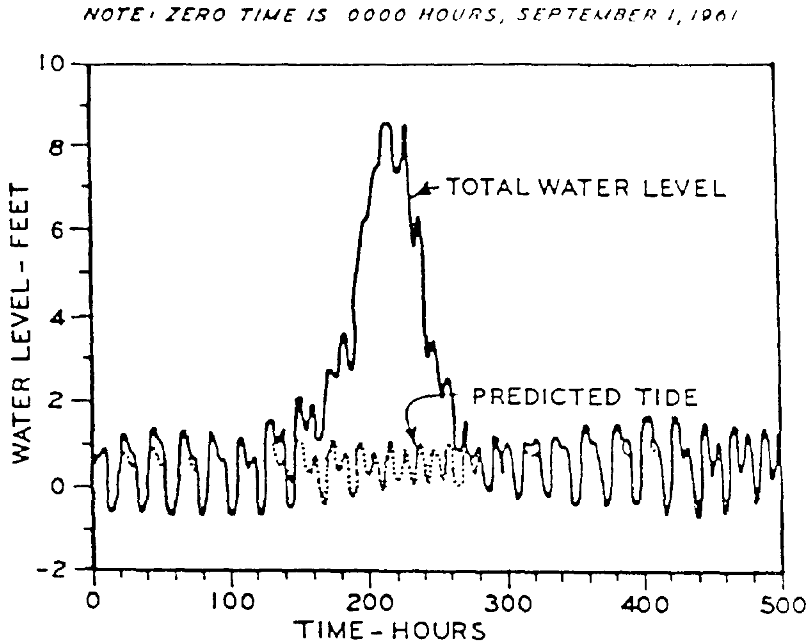
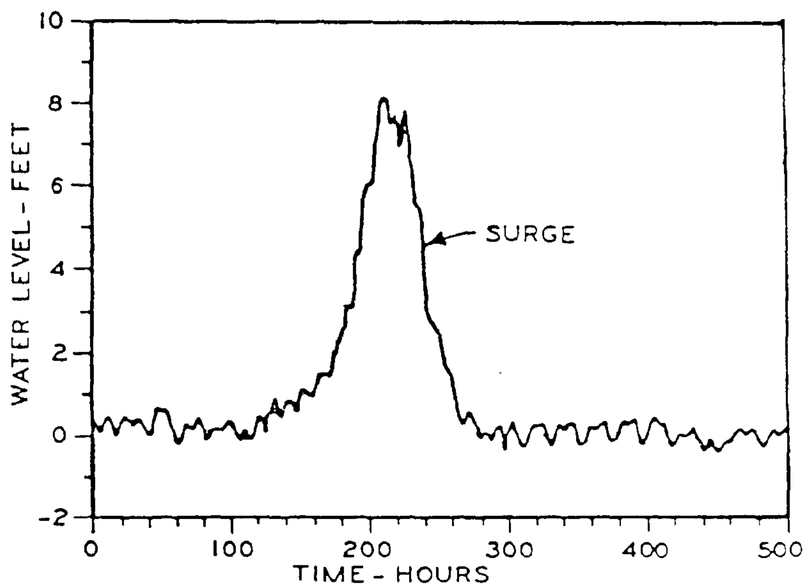


Figure 1-2. Hurricane Carla track, hourly positions, September 1961. (based on item 31 of Appendix A)



a. **Observed total water level and predicted tide**



b. **Surge obtained by extracting predicted tide from total water level**

Figure 1-3. Water level variations during Hurricane Carla (1961) at Pleasure Pier, Galveston, Texas.

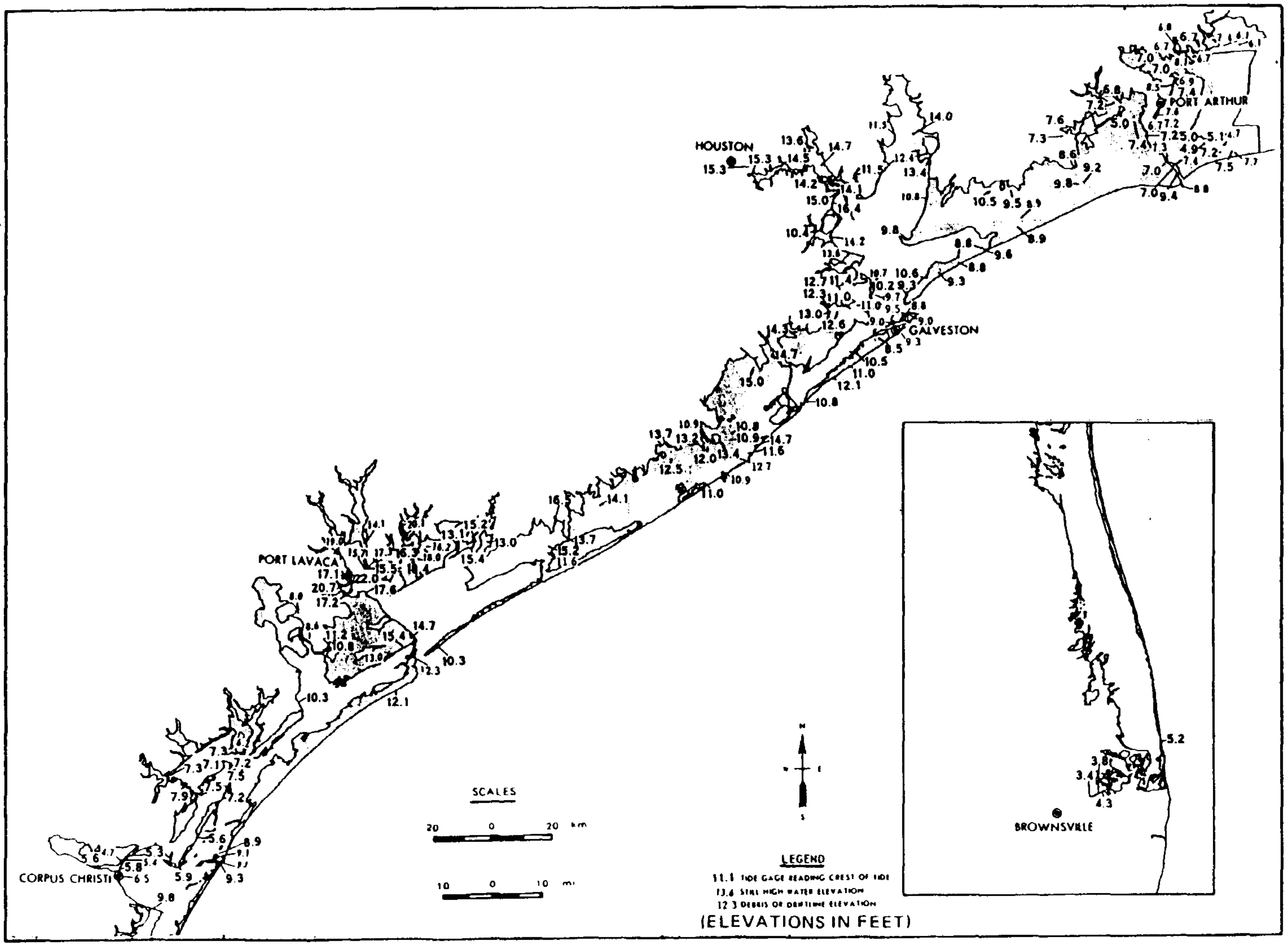


Figure 1-4. High water mark chart for Texas, Hurricane Carla, 7-12 September 1961. (Shaded area indicates the extent of flooding.) (item 23 of Appendix A)

distances due to the flat coastal terrain. Vegetation and other obstacles in these areas cause extensive energy dissipation via turbulence and bottom friction; however, some energy is pumped back into the system by the wind.

1-13. Theoretical Considerations. The fundamental equations which describe water motions associated with storm surges, tides and other shallow water wave phenomena are presented in order to emphasize the underlying physical concepts and hydrodynamic processes involved. Also, these equations provide reference to the basic framework upon which mathematical models, as discussed in the following chapter, are formulated. The basic shallow water equations may be expressed in one, two, or three dimensions depending on the number of velocity components considered. Figure 1-5 shows the velocity components u, v and w for the x-, y- and z-directions, respectively. Computations performed with three-dimensional equations are exceptionally complex and, because the vertical velocity w is small compared to the horizontal velocities, it is usually justified to use two-dimensional equations. Further simplifications can be obtained by taking the equations in one horizontal dimension--a common practice prior to the introduction

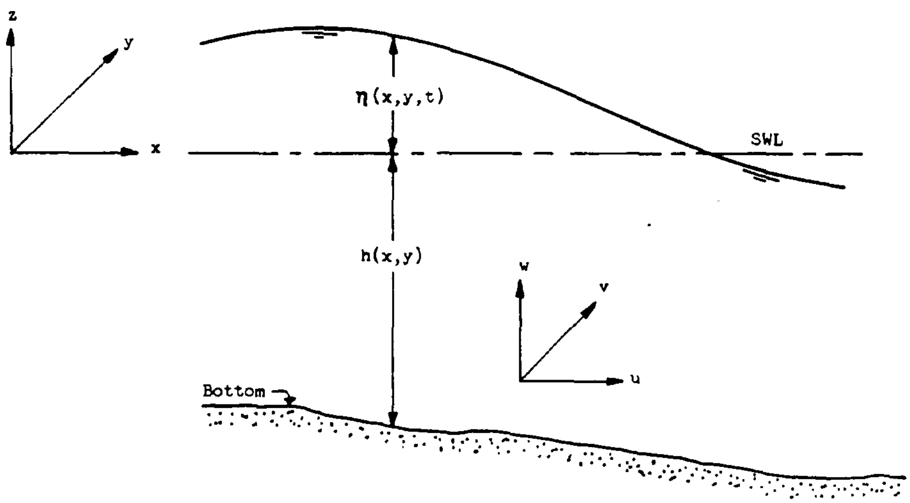


Figure 1-5. Reference frame.

of high speed computers. However, one-dimensional equations can only provide limited information with regard to the water motions. For storm surge analysis it is, therefore, recommended that two-dimensional equations be used for calculating the water motions. In the presentation that follows, the three-dimensional expressions are given first and these are reduced to the two-dimensional expressions in order to demonstrate the approximations involved in the transformation.

a. Basic Equations. In theoretical studies of shallow water waves it is convenient to derive the "equations of motion" and the "equation of continuity" based on principles of conservation of momentum (Newton's second law) and the conservation of mass in terms of a column of fluid extending from the free surface to the sea bed. In embayments and shallow sea areas the flow is nearly horizontal and, thus, the vertical accelerations are negligible (ignoring short period surface waves and flow around obstacles). Additionally, it is usually assumed the water is of uniform density. Referring to the definitions in Figure 1-5, the three-dimensional hydrodynamic equations (referred to as the Navier-Stokes equations) in the x-, y- and z- directions consistent with the previously stated assumptions are as follows:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} - fv + \frac{1}{\rho}\left(\frac{\partial p}{\partial x} - \frac{\partial \tau_{xx}}{\partial x} - \frac{\partial \tau_{xy}}{\partial y} - \frac{\partial \tau_{xz}}{\partial z}\right) = 0 \quad [1\text{-}1]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + fu + \frac{1}{\rho}\left(\frac{\partial p}{\partial x} - \frac{\partial \tau_{xy}}{\partial x} - \frac{\partial \tau_{yy}}{\partial z} - \frac{\partial \tau_{yz}}{\partial z}\right) = 0 \quad [1\text{-}2]$$

$$\frac{\partial p}{\partial z} + \rho g = 0 \qquad [1\text{-}3]$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \qquad [1\text{-}4]$$

in which u, v, w are the velocity components in the x-, y- and z-directions, respectively; p is the pressure; t is time; g is the acceleration of gravity; f is the Coriolis parameter ($f = 2\omega \sin\phi$)

is the angular velocity of the earth ($\omega = 2\pi/24$ radians/hour); ϕ is the geographical latitude; ρ is the water density; and τ_{xx}, τ_{xy}, etc., are the turbulent shear stresses. Equations [1-1] through [1-4] describe water motions in the vertical direction and two horizontal directions in which the first two relations are the equations of motion and the third relation is the hydrostatic pressure law derived from a simplification of vertical motions in accordance to the above stated assumptions. Equation [1-4] is an expression for the conservation of mass and is commonly referred to as the continuity equation. A more tractable form of these equations can be obtained by using particular transformations, boundary conditions and depth averaging. Equation [1-3] can be readily integrated to give the hydrostatic pressure distribution, hence

$$p - p_a = \rho g\,(\eta - z) \qquad [1\text{-}5]$$

in which p_a is the atmospheric pressure (usually for simplicity assumed to be zero) and η is the elevation of the water surface above the mean water level. Equation [1-5] may be substituted into Equations [1-1] and [1-2] for defining p. Applying boundary conditions at the bottom $z = h(x,y)$ and at the free surface $z = \eta(x,y,t)$, neglecting variations of u and v with z and integrating Equations [1-1], [1-2] and [1-4] over the total water depth, it is possible to write the hydrodynamic equations in two horizontal dimensions in the following form:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = fv - g\frac{\partial}{\partial x}(\eta - \xi - \zeta)$$

$$+ \frac{1}{\rho D}(\tau_{sx} - \tau_{bx}) + \frac{W_x P}{D} + \epsilon_{xx}\frac{\partial^2 u}{\partial x^2} + \epsilon_{xy}\frac{\partial^2 u}{\partial y^2} \qquad [1\text{-}6]$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -fu - g\frac{\partial}{\partial y}(\eta - \xi - \zeta)$$

$$+ \frac{1}{\rho D}(\tau_{sy} - \tau_{by}) + \frac{W_y P}{D} + \epsilon_{yx}\frac{\partial^2 v}{\partial x^2} + \epsilon_{yy}\frac{\partial^2 v}{\partial y^2} \qquad [1\text{-}7]$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial (uD)}{\partial x} + \frac{\partial (vD)}{\partial y} = R \qquad [1\text{-}8]$$

in which u, v are the depth-averaged velocities in the x, y directions; ξ is the atmospheric pressure deficit (see Appendix D), expressed as an equivalent head of water, ζ is the astronomical tide potential expressed as an equivalent head of water; W_x and W_y are the x, y- components, respectively, of the wind velocity taken at approximately 30 feet above the water surface; D is the total water depth ($D = \eta + h$); R is the rate at which water is either added to or lost from the system (i. e., as a result of precipitation, evaporation, etc.) expressed in depth per unit time; τ_{sx}, τ_{sy} are the x, y components of the surface shear stress due to the interaction between wind and water; τ_{bx}, τ_{by} are x, y components of bottom shear stress; ϵ_{xx}, ϵ_{xy}, etc. are the eddy viscosity coefficients, and P is the precipitation rate (depth/time). Generally, the wind shear stress components divided by the water density are taken in the form

$$\begin{aligned} \tau_{sx} &= kW^2 \cos\theta \\ \tau_{sy} &= kW^2 \sin\theta \end{aligned} \qquad [1\text{-}9]$$

in which W = wind speed; θ = the angle between the velocity vector and the x-axis; and k is a nondimensional windstress coefficient (usually taken to be constant or presumed to be a function of the wind speed). In terms of the surface drag coefficient C_d (e.g.,item 16), $k = C_d\ \rho_a/\rho$ where ρ_a, ρ are mass density of air and water respectively. The bottom shear stress components divided by the water density are normally taken as

$$\begin{aligned} \tau_{bx} &= K\ u\ (u^2 + v^2)^{1/2} \\ \tau_{by} &= K\ v\ (u^2 + v^2)^{1/2} \end{aligned} \qquad [1\text{-}10]$$

in which K is a bottom shear stress coefficient usually expressed in accordance to either Manning's, Darcy-Weisbach's or Chezy's resistance law. Although the previous relations were written in terms of the depth integrated velocities, these relations may also be readily expressed in terms of the vertically integrated transport per unit width--a form of the equations preferred by a number of investigators. In this case the equations of motion and continuity become

$$\frac{\partial U}{\partial t} + \frac{U}{D}\frac{\partial U}{\partial x} + \frac{V}{D}\frac{\partial U}{\partial y} = fV - gD\frac{\partial}{\partial x}(\eta - \xi - \zeta) + \frac{1}{\rho}(\tau_{sx} - \tau_{bx}) + W_x P + \epsilon_{xx}\frac{\partial^2 U}{\partial x^2} + \epsilon_{xy}\frac{\partial^2 U}{\partial y^2} \qquad [1\text{-}11]$$

$$\frac{\partial V}{\partial t}) + \frac{U}{D}\frac{\partial V}{\partial x} + \frac{V}{D}\frac{\partial V}{\partial y} = -fU - gD\frac{\partial}{\partial y}(\eta - \xi - \zeta) + \frac{1}{\rho}(\tau_{sy} - T_{by}) + W_y P + \epsilon_{xy}\frac{\partial^2 V}{\partial x^2} + \epsilon_{yy}\frac{\partial^2 V}{\partial y^2} \qquad [1\text{-}12]$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = R \qquad [1\text{-}13]$$

in which U and V are the x and y components, respectively, of the volume transport per unit width. For this form of the equations, the wind shear stress components as given by Equation [1-9] are unchanged; however, the bottom shear stress components divided by the water density are given by

$$\tau_{bx} = KU\,(U^2 + V^2)^{1/2}\,D^{-2}$$
$$\tau_{by} = KV\,(U^2 + V^2)^{1/2}\,D^{-2} \quad . \qquad [1\text{-}14]$$

b. Possible Alternate Forms of Basic Equations. The equations for motion and continuity given provide essentially a complete description of water motions associated with storm surges coupled with astronomical tides. There are a number of variations in which the basic equations may be expressed. Some of these variations are due to certain transformations made while others are due to simplifying the governing equations by neglecting the less important hydrodynamic processes. In conducting storm surge analysis it is sometimes possible to simplify the equations of motion while retaining sufficient accuracy of the estimates. Such simplifications can in some instances result in a substantial reduction in computational effort. For many problems it is possible to neglect the convective terms (i.e., the second and third terms on the left hand side of Equations [1-6] and [1-7] or Equations [1-11] and [1-12] due to their small contribution to the total processes involved. Omission of these terms make it impossible to compute circulation currents and horizontal eddies; however, such phenomena are not generally important in storm surge analysis since interest is primarily centered on the water level variations. In most cases, it is possible to neglect the eddy viscosity terms (i. e., the last two terms on the right hand side of Equation [1-6] and [1-7] or Equation [1-11] and (1-12]) if the problem simulation time is only for a few days. These terms provide a mechanism whereby energy piling up at the smallest possible scale can be removed from the system as time elapses from the initial state. The energy buildup is gradual and the terms can become important if the simulation period is carried out over a period of several days. In the event that it is possible to neglect both the convective and eddy viscosity terms, it can be usually expected that the computational effort will be reduced by as much as 25 percent. The precipitation terms in the equations of motion are also frequently neglected in storm surge calculations because of their small contributions and the fact that in most instances there is insufficient knowledge to prescribe the precipitation over the system, particularly in open water areas. It is also possible to neglect the Coriolis terms when calculating the water motions in small coastal estuaries, but these terms should always be used when calculating storm surge on the open coast since their contributions can significantly affect the resulting water levels. Due to difficulties in specifying the proper forcing for astronomical tides, particularly in the open ocean, the tide potential is usually neglected in the basic relations and accounted for separately as a component that is added algebraically to the storm surge.